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Progress in modelling agricultural impacts of and adaptations to climate change

RP Rötter[1,2], MP Hoffmann[1], M Koch[1] and C Müller[3]

Modelling is a key tool to explore agricultural impacts of and adaptations to climate change. Here we report recent progress made especially referring to the large project initiatives MACSUR and AgMIP; in particular, in modelling potential crop impacts from field to global using multi-model ensembles. We identify two main fields where further progress is necessary: a more mechanistic understanding of climate impacts and management options for adaptation and mitigation; and focusing on cropping systems and integrative multi-scale assessments instead of single season and crops, especially in complex tropical and neglected but important cropping systems. Stronger linking of experimentation with statistical and eco-physiological crop modelling could facilitate the necessary methodological advances.

Addresses
[1] University of Göttingen, Department of Crop Sciences, Tropical Plant Production and Agricultural Systems Modelling (TROPAGS), Grisebachstraße 6, 37077 Göttingen, Germany
[2] University of Göttingen, Centre for Biodiversity and Sustainable Land Use (CBL), Büsgenweg 1, 37077 Göttingen, Germany
[3] Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A31, 14473 Potsdam, Germany

Corresponding author: Rötter, RP (reimund.roetter@uni-goettingen.de)

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Introduction

The huge agricultural challenge of the 21st century to accomplish food and nutrition security for a growing world population in the face of dietary changes, declining natural resources and a changing climate with more frequent and severe extreme weather is well documented [1–3].

Whether and where we tackle the agricultural challenges, and how we manage agro-ecosystems in the future will directly affect a number of the interconnected Sustainable Development Goals (SDGs, in particular SDGs 2, 1, 3 and 13 (Zero Hunger, No poverty, Good Health and well-being, Climate Action)). Climate is already changing and increasing negative agricultural impacts by more adverse and extreme weather events have been observed [4•]. This trend is likely to continue in the future and the probability of multiple climate-induced risks impacting agricultural production is expected to increase [5], adding extra challenges to farming [[4•],7•]. These risks can be reduced by targeted adaptation measures.

To explore and *ex ante* evaluate different adaptation options, process-based crop simulation models (CSMs) have and continue to play a prominent role as they are capable to quantify the interactions of genotype, environment and management ($G \times E \times M$) and their impact on desired outputs such as yield, yield stability, carbon sequestration as well as undesired outputs such as nutrient leaching and Greenhouse Gas (GHG) emissions.

Yet, the questions of food and nutrition security [1], decision-making on adaptation to climate risks or resource management and multi-targeted policy decisions at higher aggregation levels require more complex assessments of agricultural production systems at various scales. Therefore, integrated approaches that combine biophysical and socio-economic considerations and explicitly take the goals and preferences of decision makers across different scales into account are necessary to address these emerging questions in agricultural research.

Here we first present a brief overview about the progress made in crop modelling to capture climate impacts on crop productivity and the development towards integrative assessment, for example, by combining biophysical and socio-economic analysis. Then we outline how to further improve modelling approaches, allowing for a more comprehensive and integrated assessment of agricultural impacts of and adaptations to climate change.

Modelling agricultural impacts of climate change: recent progress

Agricultural systems models, and especially CSMs [[11•],[11•]] have played a key role in assessing agricultural impacts of climate change — in particular after the 1st assessment report of IPCC [9]. However, only since 2010 substantial improvements have been made in using CSMs for that purpose, mainly driven by the AgMIP [10] and MACSUR [11•] networks. Results were presented among others at the iCROPM 2016 in Berlin [12]. Here, we concentrate on two key areas, namely modelling of potential impacts

and adaptations for single crop and integrated analysis of adaptations (farm and higher aggregation levels).

Modelling potential crop impacts and adaptations (field to global)

Building on studies on CSM deficiencies in Europe [13], the AgMIP wheat project [14] became a role model for identifying CSM shortcomings, analysing underlying causes and proposing solutions. Using 27 crop models, Asseng *et al.* [14] found that calibration could strongly reduce uncertainty and that the multi-model ensemble mean or median was found to better reproduce observed patterns than any individual model [15]. Identifying the temperature response as a major source of uncertainty, the AgMIP team then investigated the effect of high temperature and found that increasing local temperature by 1 °C will reduce global wheat yields by 5–6%, if no adaptation takes place [16••]. While ensemble approaches helped to make model predictions more robust and quantify the uncertainties, the next logical step was to improve responses to heat [17] and the fundamental temperature functions in individual models, to eventually reduce the uncertainty by proposing improved functions and parameterization [18••] (Table 1).

These and similar studies applied models at individual sites that were assumed to represent larger production regions. For global coverage, as needed for addressing land-use and trade dynamics, gridded crop simulations are conducted for the whole globe [19], also using model ensembles. This approach poses various challenges: conceptual, technical as well as for model evaluation [20•], but allows for globally consistent and comprehensive assessments.

While there is a range of studies investigating the potential impact on agricultural systems, there are far less studies exploring potential adaptation options, whereby adaptation is often not clearly separated from intensification [21]. One important field is the development of adapted varieties. Only recently have we seen studies that tackle model-aided design of crop ideotypes for well-defined environments to *ex ante* evaluate adaptation by breeding new climate-resilient crop cultivars [6,7•]. Multi-model ensembles are also useful to assess the uncertainty of genotypic adaptation options [22,23].

Integrated modelling of adaptation options from farm to global scales

As economic and integrated assessment modelling (IAM) of climate change impacts and adaptation for agriculture systems is now increasingly applied to get a more complete picture, [24,25••], CSMs continue to play a central role in this as they provide key inputs to IAM [11•,26–28]. For example, in the MACSUR pilot studies on integrated regional assessment of climate-impacts on agricultural yields and land use [29•] (Figure 1), crop models provide yield and environmental impact data to integrated "bio-economic" farm type and/or regional land use models. These look at the consequences of climate change on agricultural system performance at the farm household, landscape and regional scale, also assessing the effect of response options, that is, adaptation and mitigation measures [29•].

Perspectives/future challenges

Required exchange of insights from empirical statistical and process-based modelling

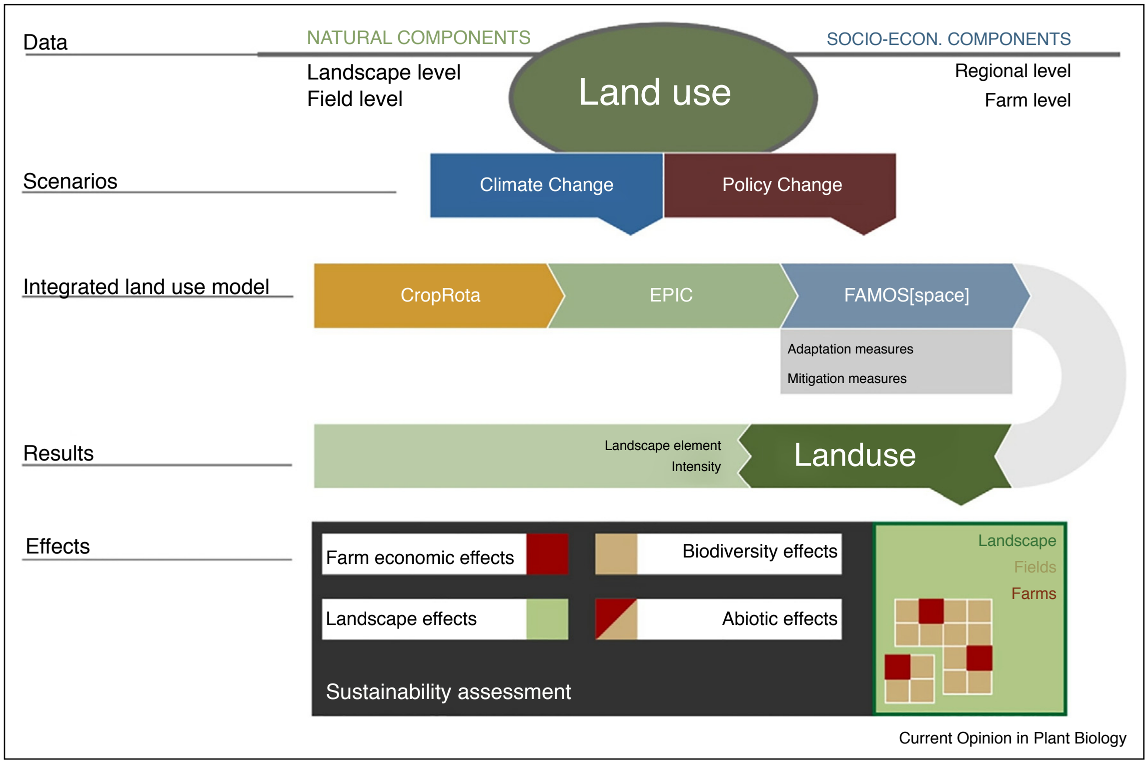
Statistical models (SMs) have been widely used to empirically examine the linkage between environmental variables and yield. Significant relationships between a wide range of climatic variables (including extremes) and crop yield have been reported [30]. One advantage of this method is that it inherently covers also indirect yield limiting factors, which are linked to climate variables, like

Table 1

Recent progress in crop model improvement The example for progress in crop modelling shows for four models to what extent revised temperature response functions improved wheat model performance regarding several output variables using statistical performance indicators RMSE (Root Mean Square Error) and modelling efficiency (EF). Reprinted by permission from Nature Publishing Group [18••]

Model	Grain yield		Total above-ground biomass		Days to maturity		Grain number	
	Original model ($t\ ha^{-1}$)	Improved model ($t\ ha^{-1}$)	Original model ($t\ ha^{-1}$)	Improved model ($t\ ha^{-1}$)	Original model (d)	Improved model (d)	Original model (grain m^{-2})	Improved model (grain m^{-2})
RMSE								
APSIM	2.99	1.23	5.91	2.38	12.3	8.3	4647	3732
SiriusQuality	1.05	0.67	2.89	1.84	11.1	11.8	4046	2886
Salus	2.00	0.88	2.56	1.85	10.1	10.7	NA	NA
WheatGrow	2.43	1.98	5.47	2.95	1.4	3.6	NA	NA
EF								
APSIM	−1.91	−0.09	−1.53	0.32	−0.10	0.62	−1.63	−0.78
SiriusQuality	−0.02	0.66	−0.14	0.46	0.32	0.41	−1.52	−0.06
Salus	0.05	0.56	s0.53	0.63	0.37	0.62	NA	NA
WhatGrow	−1.73	−0.58	−1.48	−0.71	0.99	0.93	NA	NA

Figure 1



Recent progress in integrated regional assessment of climate change impacts. The example illustrates the multi-scale approach and components of integrated modelling. Reprinted by permission from Elsevier [29•].

pest and diseases. Process-based crop models so far largely ignore their effects, and thus fail to estimate farmer yields accurately in regions and years where biotic stresses are significant. Statistical crop yield models can play an important role in hinting at mechanisms and relationships that have not been (sufficiently) covered in CSMs.

On one hand, SMs are constrained in many cases by the availability of adequate, representative yield data, and also lack information on critical interactions of factors such as weather, soil and management practices. By disentangling and quantifying the relative importance of certain yield-determining factors, CSMs can also help to improve empirical statistical models [31]. Comparative analysis of the two approaches can, hence, stimulate discussions and develop a better understanding of the major yield limitations, especially at higher aggregation levels.

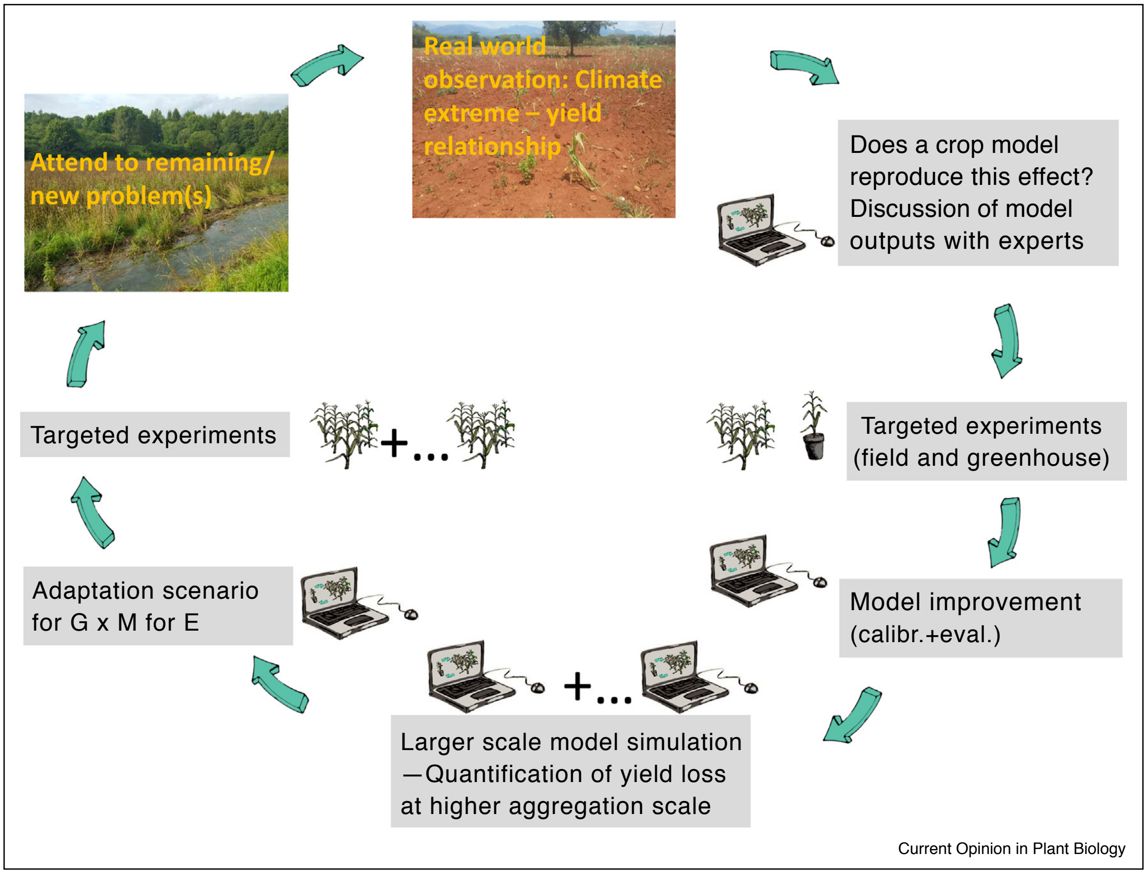
Stronger linkages of process-based modelling and experimentation

Substantial mismatches between CSMs and SMs may indicate knowledge gaps regarding the mechanisms/processes that cause under-/overestimation of yield, et cetera. To overcome these, we need to design specific greenhouse and field trials to derive more comprehensive process understanding on why CSMs fail to reproduce observed yield patterns. While the multi-model ensemble approach proposed by AgMIP/MACSUR works well to describe and narrow uncertainties, multi-model aggregates do not further our understanding of the causes [13]. While these can be the basis for systematically exploring critical parameters and assumptions [32], they do not compensate for exploring missing mechanisms [33]. Such deep knowledge can only be derived from experimental data, which need to include control treatments. Thus, there is an urgent need to develop experiments closely linked with model improvement. Good examples for such might be the mechanisms behind yield reductions by the interactions of heat and drought stress. Furthermore, CSMs, given they are well evaluated, can also be usefully applied to develop much more concrete field experiments to test innovative management options in new environments (Figure 2). Such options have hardly been explored, but could save a lot of costs/time that such experiments require.

Moving from crop to cropping system adaptations and whole farm climate-smart management

Still, by far the majority of CSMs deal with single season, single crop runs. For analyzing climate change impacts

Figure 2



Proposed cycle of linked experimentation and modelling in support of methodological advancement. The cycle illustrates the need for stronger linkages between experimentation and modelling from problem definition to verification and tackling of new research issues (own illustration). The climate extreme-yield relationship is used as an example for one possible yield reducing factor possibly not adequately captured by a crop model. Other examples could refer to biotic stresses (pest & diseases). The abbreviation G × M for E stands for genotype by management interaction for a certain environment.

this has the big disadvantage that it does not match with the reality of farmers. The latter respond to climatic risk by using, for example, conservation agriculture, cover crops, substituting crops by other ones or even using a drought-suffering crop as animal feed. For more practical relevance of model-based assessments, a cropping systems and whole farm perspective is needed [25••,34]. Combining crop modelling with remote sensing and in-season weather forecasts could inform adaptation planning [35,36]. Farmers normally make their crop management decisions (crop choice, fertilizer, plant protection, etc.) based on profitability expectation averaged over the years of their own experience, thereby missing substantial gains in favorable years [37]. Better seasonal weather forecasts, for instance of the start and end of the rainy season or of the expected rainfall pattern and amount within the season, could overcome this by guiding season-specific management practices [37,38]. Already now certain events such as El Niño-Southern Oscillation or the arrival of the Indian monsoon can be predicted fairly well, and such forecasts have been used as crop model input in several studies [39–42]. Integrated modelling approaches would eventually allow for assessing system performance and sustainability indicators (farm economics, biodiversity, etc.) at the regional level (Figure 1).

Besides the focus on crop yields, there is also an increasing interest in the role that agricultural management has on environmental impact, such as carbon sequestration or GHG emissions. However, carbon stocks need years to build up, thus long-term simulation over multiple years that also reflect the current deviation from the equilibrium state are necessary to capture that. Despite some efforts, the effect of tillage on carbon storage has so far only been modelled with limited success [43], mainly due to insufficient field data to develop mechanistic descriptions in the models. Economic models need to be combined with CSMs in whole-farm assessments to better evaluate management practices [25••,44].

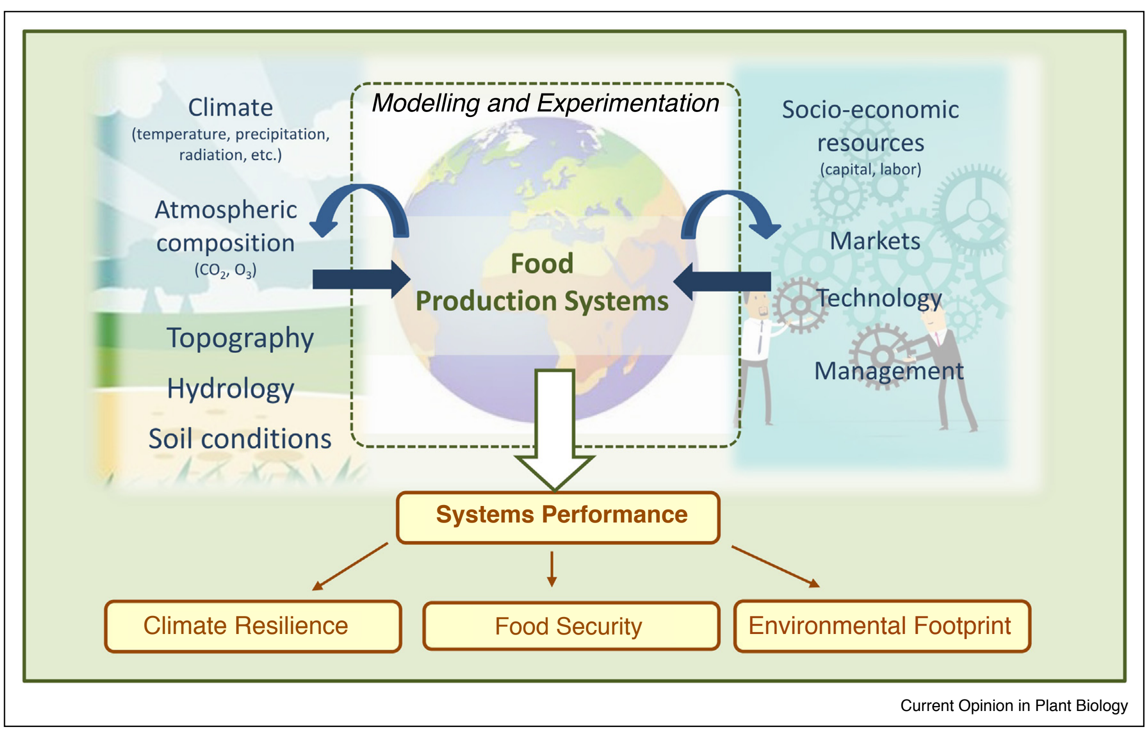
At larger scales, CSM is severely hampered by lack of data for parameterization and calibration and management systems are often unknown [20•]. Large uncertainties persist — especially related to variability in managerial practices and spatial response patterns.

Management and land use does not only respond to climate change, but also to changing socio-economic conditions, such as liberalization of markets or changes in dietary habits. CSM thus needs to be integrated into a larger modelling framework. The Coordinated Global Regional Assessments (CGRA) project of AgMIP set out to implement such multi-scale integrated assessment frameworks, which also offer insights on where inconsistencies exist between scales and disciplines so to understand and address them.

Specific challenges in assessing climate change impacts and adaptations of tropical plant production systems

Global model runs suggest strong effects of climate change on the crop production systems in the Global South, especially in Africa [1,8]. However, such runs were done mainly for water limited and/or nutrient-limited yield, hence, with yields not limited by biotic stresses. That makes the results of little use to understand the actual effect of climate change on these systems, as many tropical plant production systems are heavily restricted by combinations of severe abiotic and biotic stresses, with yield gaps often exceeding 80% [45]. Thus, we need much better understanding of how climate effects scale with changes in low input systems. Moreover, many tropical systems are arguably more complex including agroforestry/intercropping. Unfortunately, crop models have been rarely tested/applied in such systems. Likewise, important tropical crops have been much less investigated in experiments regarding their exposure to agro-climatic extremes than those for temperate systems [31]. Even with some progress in data availability [46], there is a need for both — more experiments and modelling — (as propagated by TROPAGS, see Figure 3) to understand the underlying mechanisms. Concurrently, it is required to account for the high diversity of conditions that cannot all be tested in field experiments, especially in complex tropical production systems. A key constraint to realistically upscaling the productivity of such systems (and how it is affected by climate change) to region level is, for instance, that fields of smallholder systems are not clearly defined, and a wide range of crop types can be found within a field. Moreover, many systems are integrated crop-livestock systems, which makes the common

Figure 3



Analytical framework of the Divison Tropical Plant Production and Agricultural Systems Modelling (TROPAGS) with linked modelling and experimentation at the core. The TROPAGS analytical framework illustrates the relevant inputs and outputs for an integrated analysis of climate change impacts on food production systems and *vice versa*. Furthermore it is meant to underpin the principle of ‘no modelling without experimentation’ and complement it with ‘no experimentation without modelling’. While this framework offers an overall perspective and guidance, it should be kept in mind that the analysis requires tailoring to local socio-economic and biophysical conditions through strong collaboration with farmers and relevant other stakeholders (own illustration).

use of the model output variable 'yield produced per unit area' difficult.

This diversity found in smallholder systems serves, among others, as an insurance against drought risk. Secondly, the diversity of the crops offers the opportunity for a balanced diet with sufficient nutrients, vitamins, et cetera which is crucial for food security. So far, crop models are not capable of capturing the multi-species interactions within one 'field' and the associated services delivered. Besides improving crop models, fast track methods are needed to characterize and inventory smallholder fields as a basis for upscaling. Thereby the typical simplistic focus of modelling climate change impacts on sole crops (usually maize) in smallholder systems of Africa [47] can be overcome. Remote sensing is of potential interest, but faces considerable challenges in identifying and differentiating plant species [48,49].

Conclusions

Considerable progress has been made in projecting climate impacts on major cropping systems, especially for wheat, maize and rice from plot to global scale. Here data assimilation techniques based on CSM and remote sensing or multi-model ensembles have been applied. For more practical relevance to farmers and decision makers for adaptation, mitigation and production planning, CSM need to be integrated with economic modelling and need to better reflect whole-farm and complex production systems. For this, improvement of mechanistic understanding of climate impacts on crop growth, that is, better linking of experimentation and CSM, and better data on management conditions, especially in complex tropical systems will be required. CSM and experiments need to work together to promote mutual understanding and to facilitate upscaling of experimental findings.

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